N93-26988

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THRUSTER MODELS FOR NEP SYSTEM ANALYSIS

NUCLEAR PROPULSION TECHNICAL INTERCHANGE MEETING

PLUMBROOK STATION

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OCTOBER 22, 1992

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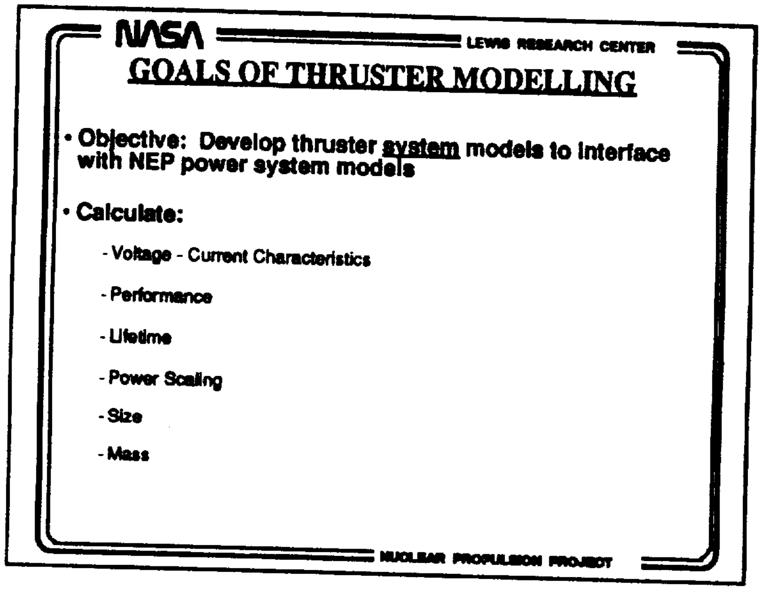
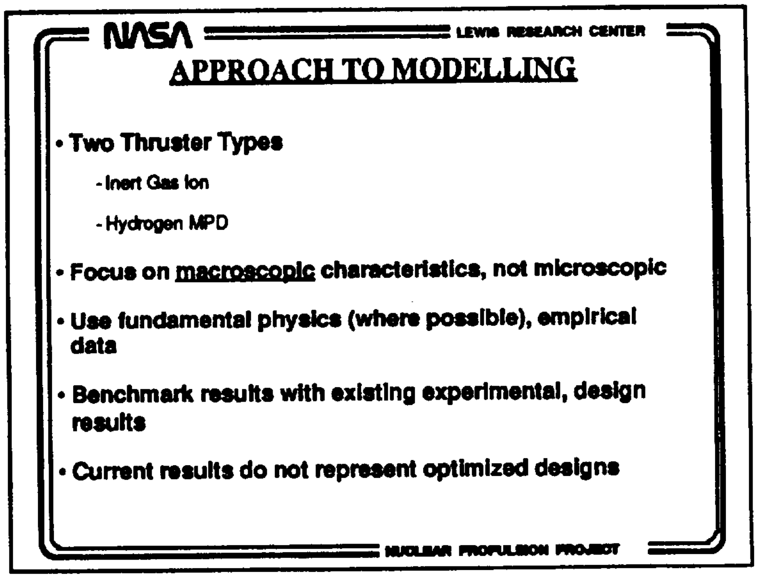


GOALS OF THRUSTER MODELLING

There are currently no thruster modelling codes that can be integrated with power system codes for full propulsion system modelling. Most existing thruster models have been written from a "stand alone" viewpoint, assuming the user is performing analyses on thruster performance alone. The goal of the present modelling effort is to develop thruster codes that model performance and scaling as a function of mission and system inputs, rather than in terms of more elemental physical parameters.

System level parameters of interest are performance, such as specific impulse and efficiency; terminal characteristics, such as voltage or current; and mass. Specific impulse and efficiency couple with mission analyses, while terminal characteristics allow integration with power systems. Additional information on lifetime and operating may be required for detailed designs.



APPROACH TO MODELLING

For this initial effort, the two thruster types with the strongest development background are being modelled: the Magnetoplasmadynamic (MPD) and Ion Thrusters. The emphasis is on modelling these devices as systems; that is, to focus on the macroscopic system level parameters such as power, thrust, specific impulse , rather than on the microscopic parameters such as electron temperature, ionization fraction, and plasma instabilities. Where possible, the fundamental physics of the concept are used, to provide as close an understanding of the underlying processes as possible. Where understanding is incomplete, or too complex for productive system analysis, empirical results have been used. For example, applied field MPD thruster thrust generation is based on experimental measurements, rather than an analytical model.

As these models are developed, they are and will be compared to experimental data and point studies.

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MPD Thruster

- **Description**
  - Cylindrical Anode, Cathode
  - Applied Solenoidal Magnetic Field
  - Heat Pipe/Graphite Radiator
- **Constraints**
  - Cathode Life (Limits Temperature, Current Density)
  - Waste Heat Conduction Through Anode
  - Material Temperature Limits
  - Regenerative Cooling of Hyperconducting Magnet Coil
- **Inputs**
  - Performance: Power, Isp, Efficiency
  - Initial Guess on Dimensions
  - Centerline Applied Field Strength
  - Magnet Coil Size
  - Empirical Thrust Coefficient
  - Electrode Work Functions

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MPD Thruster

The MPD thruster accelerates a plasma propellant through the electromagnetic Lorentz body force. The system considered in this modelling activity is a cylindrical, coaxial thruster, with an external anode and central cathode. Acceleration is provided through the interaction of radial and azimuthal currents with both the self-induced (azimuthal) and applied (axial and radial) magnetic fields. The applied field is generated by a solenoidal coil located externally of the anode. The majority of the thruster's waste heat has been observed to be deposited in the anode, requiring a radiator to reject this energy to space. In this design, the radiator is a set of lithium heat pipes conductively coupled to the anode and transferring the heat from the anode surface to a surrounding circular graphite surface.

Constraints on MPD thruster operation are cathode lifetime due to mass loss, the ability to reject the anode heat, material temperature limits, and the cooling of the hyperconducting magnet coil, which operates at 21 K

- **Inputs range from performance requirements to some system design parameters.**

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MPD Thruster Model Benchmark

Performance: 2.5 MWe, 5000 s, η = 0.5, B0 = 0.5 T

	Design+	Model
Anode Radius (cm)	15	15
Cathode Radius (cm)	2.5	2.5
Anode Length (cm)	30	30
Cathode Length (cm)	10	10
Current (kA)	10	8.5
Voltage (V)	250	295
Magnet Current (A)	2300	2471
Anode Temperature (K)	1400	1861
Anode Fall Voltage (V)	25*	90**
Radiator Area (m2)	1.1	4.4
Mass (kg)	~337#	993
Mass w/o Radiator (kg)	~132#	117

+Myers, et al. "Multimegawatt MPD Thruster Design Considerations," 9th Symposium on Space Nuclear Power Systems, 1992

*Assumed **Estimated #From a Related Study of a Flared Anode Thruster

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MPD Thruster Model Benchmark

An initial benchmarking of the code in terms of system level parameters has been performed. The point design is actually a combination of results from two references: "Multimegawatt Electric Propulsion System Design Considerations,"AIAA 90-2552; and "Multimegawatt MPD Thruster Design Considerations," in the 9th Symposium on Space Nuclear Power Systems, January, 1992. MPD thruster mass was taken from the first reference, which actually used a flared anode, with an inital anode radius of 15 cm flaring to 30 cm at the exit. The second reference is a cylindrical anode of 15 cm radius. The second reference was used for input data to the MPD model.

In terms of terminal characteristics and magnet design, the model results are reasonably close to the point design. Such differences that do exist are due to differences in assumptions of applied field thruster performance, and could be remedied through better empirical parameters in the model.

Model results differ primarily in terms of radiator mass. This is because of the difference in anode heating between the two cases. The reference case assumed a low (25 V) anode drop, whereas the MPD model estimates a 90 V drop. This difference shows up in both the radiator size and the anode temperature. An improved model of MPD thruster loss mechanisms will be required to resolve this difference.

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MPD Thruster Example

Inputs:

Power	2.5 MWe
Magnetic Field	0.1 - 0.5 T
Isp	4000 - 6000 s
Efficiency	0.4 - 0.6

Outputs:

- Anode, Cathode Dimensions
- Current, Voltage
- Electrode Temperatures
- Magnet Size, Current
- Radiator Size, Mass
- Thruster Mass

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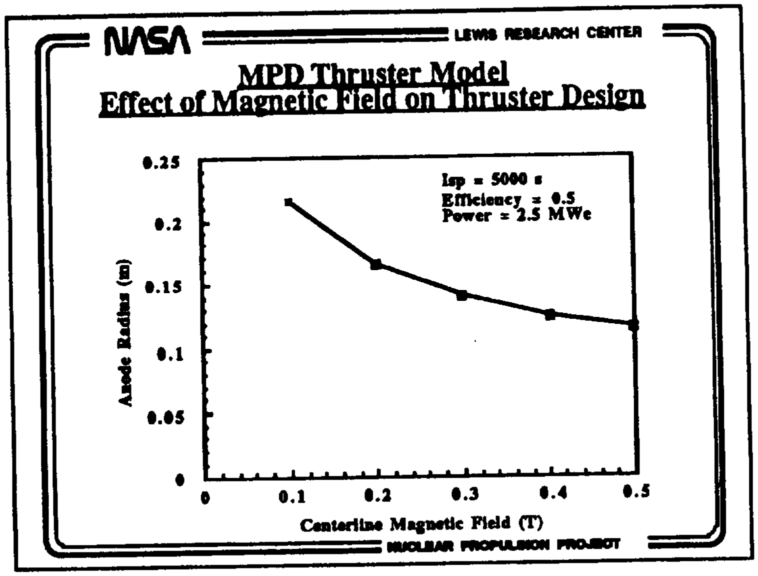
MPD Thruster Example

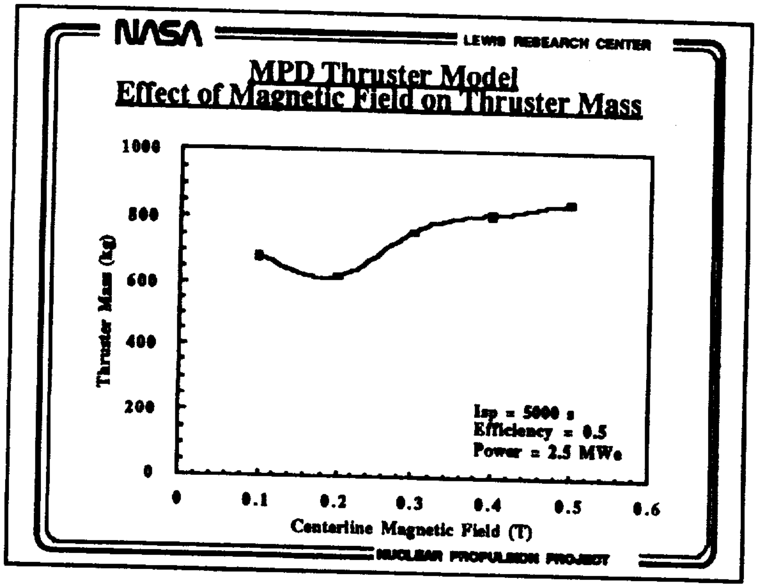
An example of the MPD code results has been generated for a range of pertinent parameters. Although a great many variables are output, only some of the more interesting results are presented herein. The power level, specific impulse, and efficiency are representative of thruster performance useful for lunar or Mars mission applications.



MPD Thruster Model
Effect of Magnetic Field on Thruster Design

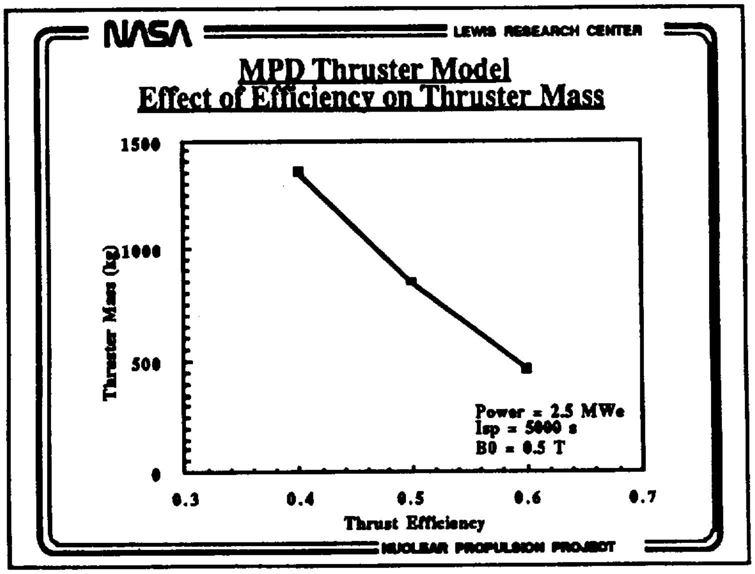
The impact of the applied field upon thruster design is shown in this figure. Increasing the applied field increases its contribution to accelerating the propellant, reducing the need for the self field thrust component. This results in a decrease in anode radius, for conditions of constant power and efficiency. This effect is seen to become less marked at higher fields, indicating that there may be maximal field strength for MPD thruster operation.

This result indicates one benefit of the model: previously, scaling of the thruster with field strength had not been addressed on a parametric basis. Instead, a single design point of field strength and anode radius was selected. It should be noted that this anode radius is also consistent with anode heat rejection and heat conduction constraints.



MPD Thruster Model
Effect of Magnetic Field on Thruster Mass

The scaling of thruster system (anode, cathode, magnet, radiator) with applied field is shown here. The result indicates a region of field strengths with minimal thruster system mass. In the present model, radiator mass is a dominant segment of the design. The minimum mass point is due to a trade off in decreased anode and magnet size with increased anode losses at higher fields. This behavior is dependent upon the anode loss assumptions, currently an area of experimental and theoretical investigation. An improved anode loss model will ensure the minimum mass point. The MPD model is amenable to incorporating such changes as they become necessary.



MPD Thruster Model
Effect of Efficiency on Thruster Mass

The dominance of radiator mass in the overall system mass is seen in this calculation of thruster mass for varying efficiencies. Increased efficiency is simply decreasing the amount of waste heat delivered to the anode. Additional effects due to thruster or magnet radius are subsumed in the radiator effects.

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Ion Thruster

- **Description**
  - Two Grid Optics
  - Current Analysis Calculates Area, Not Shape of Optics
  - Inert Gas Propellants - Xenon, Krypton, Argon
- **Constraints**
  - Space Charge Limits
  - Span-to-Gap Ratio Limits on Grid Size
  - Maximum Electric Field = 2 MV/m
  - Discharge Chamber Thermal Loading
  - Screen Grid Lifetime (TBD)
  - Accel Grid Lifetime (TBD)
- **Inputs**
  - Propellant
  - Isp, Power
  - Maximum Span-to-Gap Ratio
  - Maximum Total Voltage

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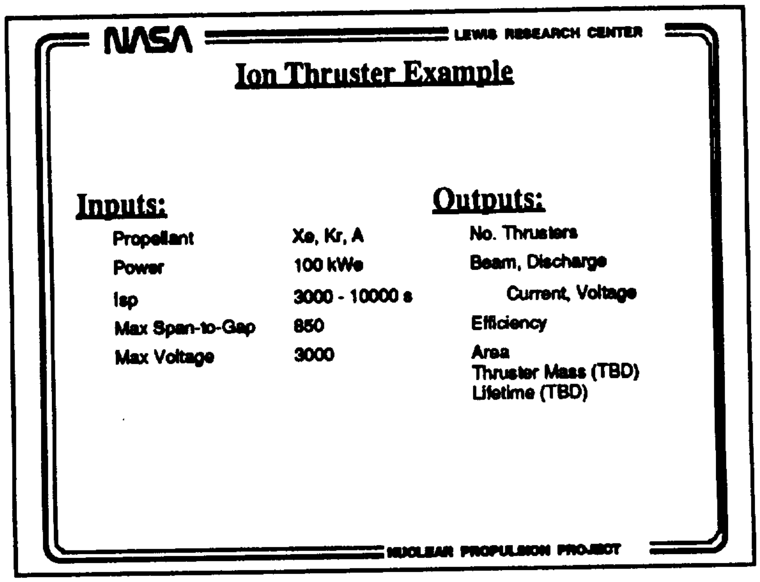
Ion Thruster

The ion thruster generates thrust through the electrostatic acceleration of a plasma propellant. The electrostatic field is generated via two grids, placed downstream from a discharge chamber in which the plasma is generated. Propellants of choice are the inert gases xenon, krypton, and argon. Propellant choice depends upon the specific impulse and efficiency required.

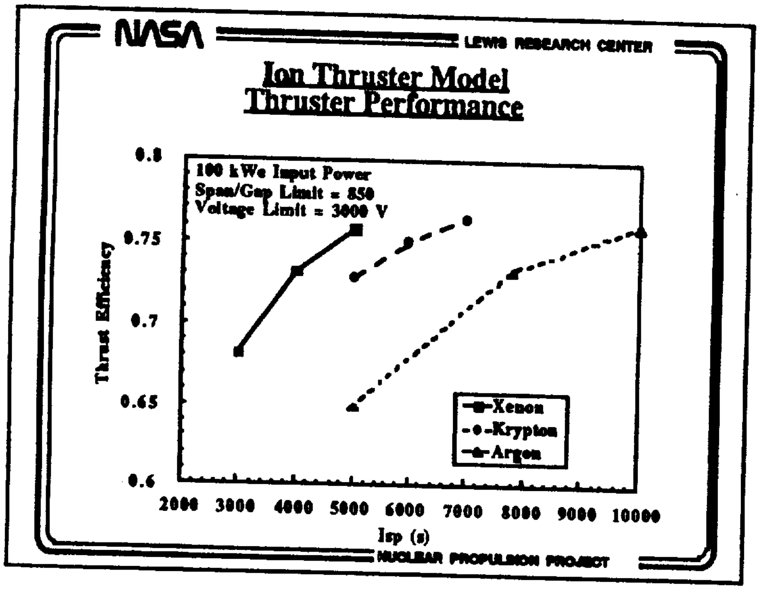
Ion thrusters operate under several constraints. The primary limit is the space charge limit upon ion beam density. In addition, numerous engineering level constraints upon power density exist, such as grid lifetimes. These considerations are functions of propellant and operating conditions. Of the constraints listed here, all but grid lifetime have been addressed in the thruster model to date.

Some constraints are based on engineering concerns, such as the span-to-gap ratio. This is the ratio of the thruster grid length (the span) to the inter-grid spacing (the gap). Due to thermal and electric deformation, there is a practical upper limit to this ratio for thruster fabrication.



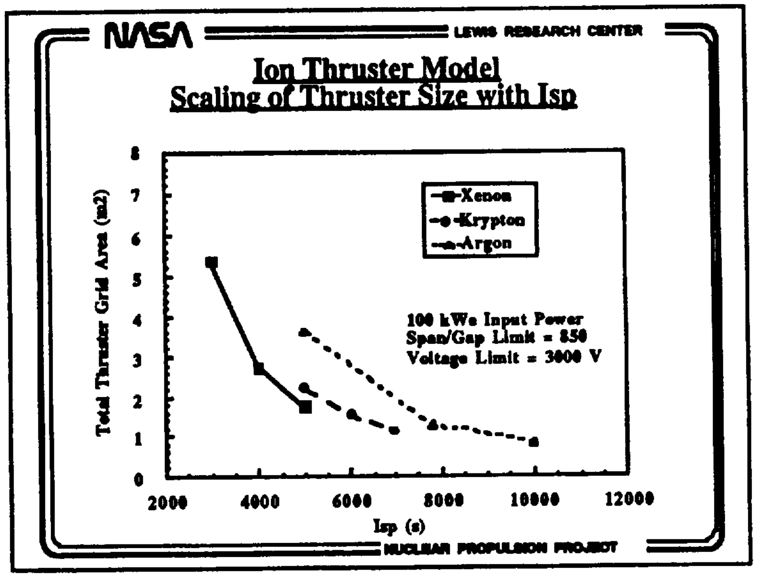
Ion Thruster Example

A sample case of a 100 kWe ion propulsion system has been assessed for this presentation. Inputs are shown above. The ion thruster model was used to calculate system parameters and operating conditions that both met the input requirements and satisfied the constraints. The thruster model will ultimately calculate thruster masses, as does the MPD model.



Ion Thruster Model
Thruster Performance

Ion thruster performance (efficency, specific impulse) is shown for all three propellants. These results are comparable to experimental data for 30 or 50 cm diameter thrusters operated at Lewis Research Center. It should be noted that these data were not generated for fixed thruster dimensions; rather, thruster scaling was an output of the model.



Ion Thruster Model
Scaling of Thruster Size with Isp

Thruster scaling is shown for the three propellants. Total grid area is the area required to process 100 kWe of power, although the number of thrusters changes with specific impulse. The model predicts greater power densities at higher specific impulse, as is seen in experiment. The behavior of these data may change after grid lifetime constraints are imposed.

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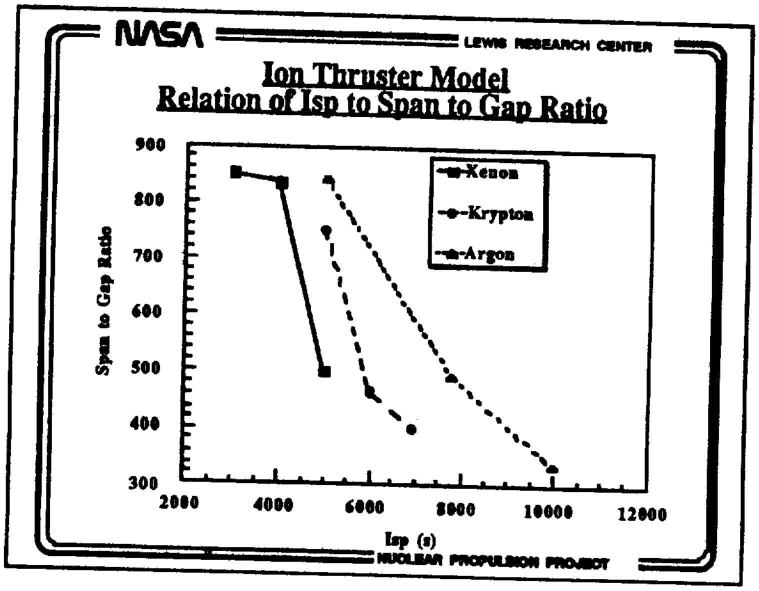

Ion Thruster Model
Relation of Isp to Span to Gap Ratio

The required span-to-gap ratios for each operating point are shown. As power density increases, the total area required decreases, allowing reduced span to gap ratios. This graph is intended as an example of the variations in parameters to be expected in a design study; the variation of other parameters such as number of thrusters, and total voltage would have to be examined in a true system analysis.

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Summary of Progress

- Development of system level thruster models is underway
- MPD and Ion thruster models are aimed at integration with power system and trajectory codes for trade analyses
- An initial "End-to-End" MPD thruster model has been developed and compared to point designs and experiment
- An initial ion thruster model is under development
- Both models have the potential for additional refinement through the use of more complex computer codes where needed; however, simplicity is desirable for rapid trade studies

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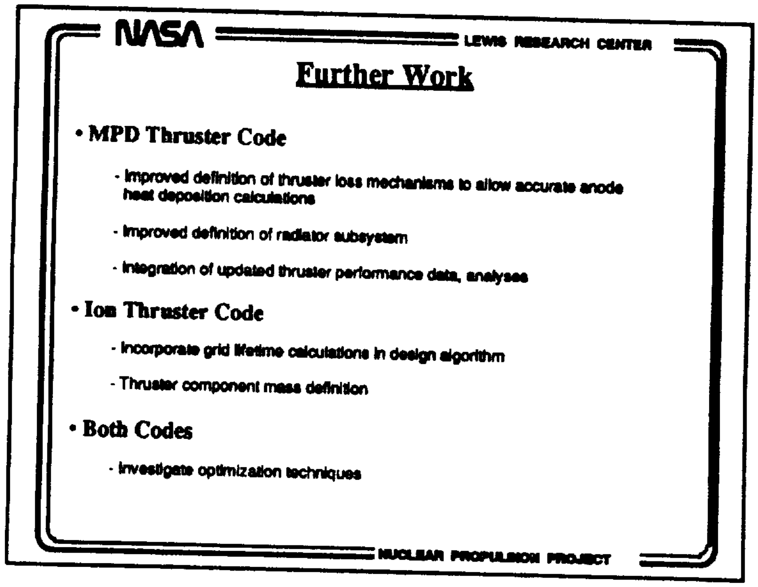
Summary of Progress

This presentation is intended as a status report on thruster system modelling efforts currently underway at Lewis Research Center. An evolutionary approach is being taken in developing these models. Refinement of the codes and their component subroutines is expected in the coming months. First order modelling has provided some initial insights into thruster behavior and requirements for effective implementation.



Further Work

In addition to completing the ion thruster code lifetime and mass models, several areas for improvement of both codes are evident. The impact of the MPD power loss models upon thruster design emphasizes the need for a better understanding, either theoretical or empirical, of dissipation in the MPD thruster. Further refinement of the radiator model is required for effective system design.

In both codes, the potential for internal optimization of certain thruster components is very strong. For example, optimization of the MPD thruster's applied magnetic field strength for minimum thruster system mass might be included in the analysis. Similarly, optimization of the ion thruster voltages, grid spacing, and grid area could be included in the analysis.

Perhaps most important at this stage is that thruster system models are being developed that allow rapid analysis while providing some understanding of the physical processes involved.